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High-Field de Haas-van Alphen Effect in non-centrosymmetric $CeCoGe_3$ and $LaCoGe_3$

Ilya Sheikin*, Pierre Rodiere[1], Rikio Settai[2], and Yoshichika Ōnuki[2]

Grenoble High Magnetic Field Laboratory, CNRS, BP 166, 25 Av. des Martyrs, 38042 Grenoble, France
[1]*Institute Néel, CNRS-UJF, 25 Av. des Martyrs, 38042 Grenoble, France*
[2]*Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*

We report on de Haas-van Alphen effect measurements in the non-centrosymmetric systems $CeCoGe_3$ and $LaCoGe_3$ in magnetic field up to 28 Tesla. In both compounds, two new high frequencies were observed in high fields. The frequencies were not detected in previous lower field measurements. The frequencies do not originate from magnetic breakdown, and, therefore, are likely to be intrinsic features of the compounds. In $CeCoGe_3$, the corresponding effective masses are strongly enhanced, being of the order of 30 bare electron masses.

KEYWORDS: $CeCoGe_3$, $LaCoGe_3$, non-centrosymmetric, de Haas-van Alphen effect

Following the discovery of superconductivity in the non-centrosymmetric heavy-fermion compound $CePt_3Si$,[1)] materials without inversion symmetry in their crystal structure have attracted a lot of experimental and theoretical interest. The interest is mainly due to a fascinating theoretical prediction[2,3)] that superconductive pairing in such systems requires an admixture of a spin-singlet with a spin-triplet state. Subsequent observation of superconductivity in other non-centrosymmetric compounds $CeRhSi_3$,[4)] $CeIrSi_3$,[5)] $CeCoGe_3$,[6,7)] and $CeIrGe_3$[8)] has further stimulated the research efforts. Very unusual superconducting properties were indeed observed in some systems, such as enormously high upper critical field in $CeIrSi_3$[9)] and $CeRhSi_3$.[10)]

The absence of inversion symmetry in the crystal lattice of a metal brings about a strong spin-orbit coupling, which in turn leads to the splitting of the electronic energy bands. The Fermi-surface of such a metal is, therefore, also split into two surfaces characterized by different chirality. This naturally results in the appearance of two distinct frequencies in the spectra of de Haas-van Alphen (dHvA) oscillations. It was demonstrated theoretically,[11)] that the analysis of the oscillatory spectra in such materials provides a direct measure of the strength of the spin-orbit coupling. It is thus very important to obtain detailed and precise dHvA frequencies and their angular dependence in materials without inversion center. In most non-centrosymmetric compounds this coupling is extremely strong being of the order of 1000 K.

$CeCoGe_3$ and its non-4f analog $LaCoGe_3$ crystallize in the tetragonal $BaNiSn_3$-type crystal structure. $CeCoGe_3$ is a moderate heavy-fermion system with a Sommerfeld coefficient of the specific heat $\gamma = 0.032$ J/molK^2. It undergoes an untiferromagnetic transition at $T_{N1} = 21$ K, followed by two more transitions at $T_{N2} = 12$ K and $T_{N3} = 8$ K.[12)] Three consecutive metamagnetic transitions were observed for magnetic field applied along the easy magnetic c-axis. The high pressure phase diagram of $CeCoGe_3$ is quite complicated demonstrating six different phases.[13)] Magnetic order vanishes around 55 kbar, and superconductivity is observed in the range of 54-75 kbar.

The dHvA effect in $CeCoGe_3$ and $LaCoGe_3$ was previously investigated in magnet fields up to 17 Tesla.[14)] In both compounds, four fundamental frequencies were identified, all of them split due to spin-orbit interaction. The frequencies themselves and their angular dependencies are similar in both compounds and are in a rather good agreement with the results of theoretical band structure calculations performed for $LaCoGe_3$. As compared to other non-centrosymmetric compounds, the splitting of dHvA frequencies in $CeCoGe_3$ and $LaCoGe_3$ is relatively small, implying a moderate spin-orbit coupling of about 100 K. In $LaCoGe_3$, all the dHvA frequencies were doubled implying either a slightly unperfect quality of the sample or a field dependence of the frequencies. The highest effective mass observed in $CeCoGe_3$ is 12 bare electron masses corresponding to the β-branch. Finally, only one frequency originating from the α-branch representing the biggest Fermi surface was initially observed in $CeCoGe_3$.[15)]

We present here the results of the dHvA effect measurements in non-centrosymmetric $CeCoGe_3$ and $LaCoGe_3$ in magnetic fields up to 28 Tesla produced by a resistive magnet in GHMFL. The measurements were performed on single crystals similar to those studied by Thamizhavel *et al*.[14)] The details of crystals preparation and characterization are given elsewhere.[12)] The measurements were performed using a torque cantilever magnetometer. The magnetometer was mounted in a top-loading dilution refrigerator equipped with a low-temperature rotation stage.

Figure 1 shows the oscillatory torque and the corresponding Fourier transform in $LaCoGe_3$ in field from 20 to 28 Tesla. All the previous dHvA frequencies[14)] can be clearly identified, and their values are very close. The most remarkable difference with lower field measurements is the observation of two new fundamental frequencies denoted as A and B in figure 1. The new frequencies, $F_A = 14.1$ kT and $F_B = 21$ kT, are considerably higher than the highest frequency, $F_\alpha = 9.15$ kT, reported for lower fields.

The dHvA oscillations observed in $CeCoGe_3$ between 20 and 28 T are shown in the upper panel of figure 2. Like in $LaCoGe_3$, all the fundamental frequencies previously observed in $CeCoGe_3$ are still present at high field (lower panel of figure 2). In addition, both components of the α-branch are

*E-mail address: ilya.sheikin@grenoble.cnrs.fr

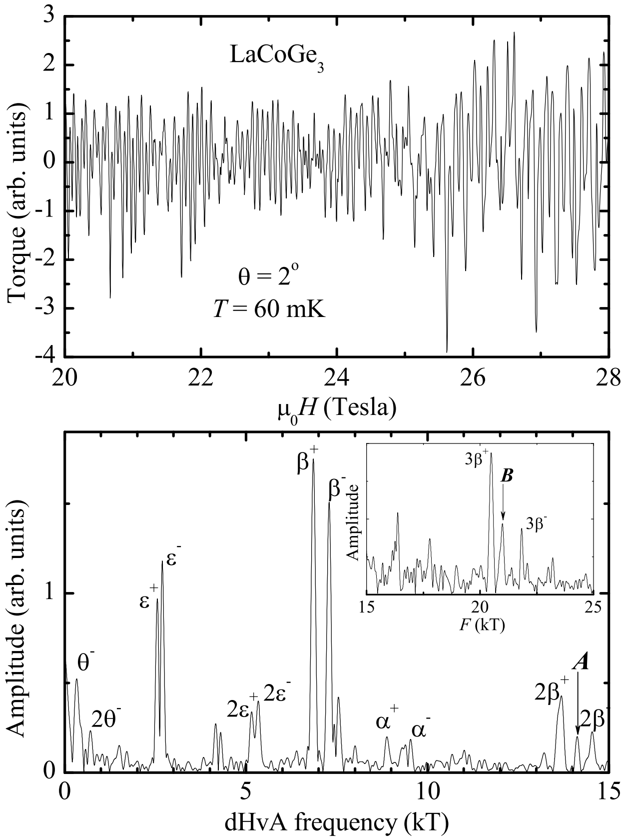

Fig. 1. High field (20–28 T) dHvA oscillations (upper panel) and its Fourier spectrum (lower panel) in $LaCoGe_3$ for magnetic field applied at 2° from the c-axis at 60 mK. The frequencies that were observed in the previous lower-field measurements are denoted by Greek letters, while the new frequencies observed at high field only are denoted A and B.

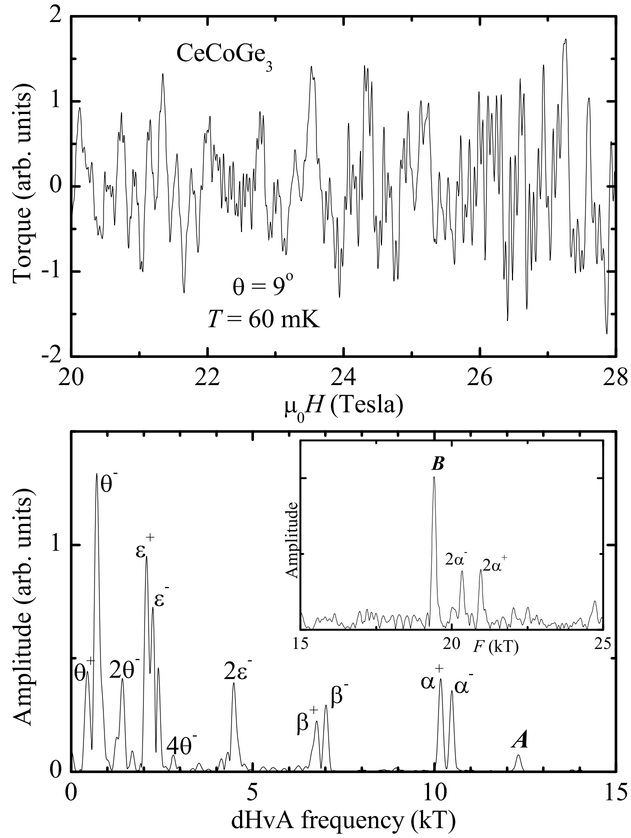

Fig. 2. dHvA oscillatory signal (upper panel) and its Fourier spectrum (lower panel) observed in $CeCoGe_3$ with magnetic field (20–28 T) applied at 9° from [100] to [110] at $T = 60$ mK. The frequencies denoted θ, ϵ, β and α were observed in the previous lower field measurements (with the exception of α^+-branch). The frequencies denoted A and B are observed only at high field and were not detected in the previous measurements.

now clearly resolved. With magnetic field applied at 9° from the crystallographic c-axis, the two frequencies are close to each other, $F_{\alpha^+} = 10.17$ kT and $F_{\alpha^-} = 10.47$ kT. The most significant result, however, is the presence of the new frequencies, A and B, in the Fourier spectrum of $CeCoGe_3$. The frequencies are somewhat lower than in $LaCoGe_3$ being $F_A = 12.31$ kT and $F_B = 19.42$ kT. Like in $LaCoGe_3$, both new frequencies are fundamental.

Figure 3 shows the temperature dependence of the dHvA amplitudes of the new frequencies A and B as well as α and β-branches in $CeCoGe_3$ for magnetic field applied at 9° from the crystallographic c-axis, the same orientation as in figure 2. These data allow one to determine effective masses by fitting the experimental points to the temperature-dependent part of the Lifshits-Kosevich formula.[16)] The best fits to the formula along with the extracted effective masses are also shown in figure 3. It was previously reported[14)] that α and β-branches possess the highest effective masses of 8 and 12 bare electron masses respectively. These values are very close to the current results if only the α^- frequency is considered and taking into account that only a single frequency from the α-branch was initially observed in previous measurements. Interestingly, the affective masses of the two frequencies originating from the α-branch differ by a factor of more than two, being 14.9 and 7.3 bare electron masses for α^+ and α^- frequencies respectively. This is in contrast with all the other branches where the effective masses of the two components are quite close to each other. The most surprising result, however, is that the effective masses of the new frequencies are strongly enhanced being 27 and 31 bare electron masses for A and B respectively. These values by far exceed the masses of the other previously observed frequencies.

Figure 4 shows the angular dependence of the dHvA frequencies in $CeCoGe_3$ for the magnetic field rotation from [001] towards [100] direction. The frequencies were determined from the Fourier transform over the field range from 20 to 28 Tesla. The angular dependence of the frequencies observed at lower fields is very similar to the previously reported one.[14)] The highest of the new frequencies, B, exists only over a small angular range at about 10° from the c-axis. The other new frequency, A, however, is observed over an angular range of about 15° and is centered around the c-axis.

It is not perfectly clear whether the new dHvA frequencies A and B observed both in $LaCoGe_3$ and $CeCoGe_3$ emerge only at high field above 17 T or exist at lower fields as well, but can not be detected due to experimental limitations. Very small amplitudes of the corresponding oscillations as well as strongly enhanced effective masses found in $CeCoGe_3$ make the latter scenario quite possible. In $LaCoGe_3$, however, while

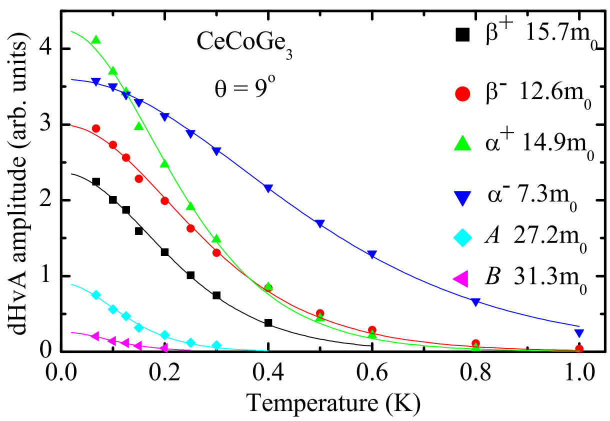

Fig. 3. (Color online) Temperature dependence of the dHvA amplitude is shown for α and β-branches as well as the new frequencies A and B of $CeCoGe_3$ with magnetic field applied at 9° from c to a-axis. Lines are the fits to the temperature dependent part of the Lifshits-Kosevich formula $A(T) \propto \frac{\alpha m^* T/B}{\sinh(\alpha m^* T/B)}$, where $\alpha \approx 14.69$ T/K. The effective masses, m^*, obtained from the fits are also shown. m_0 is the bare electron mass.

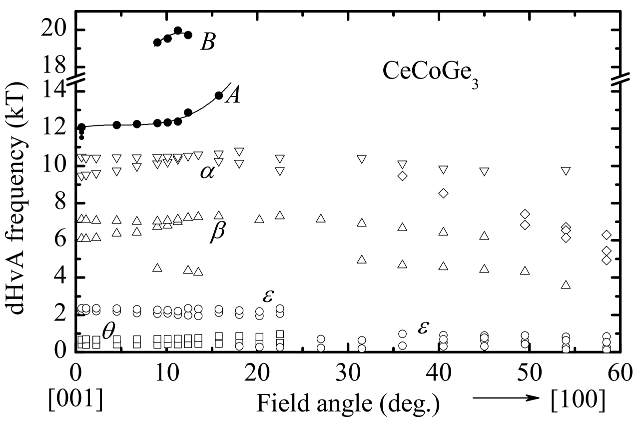

Fig. 4. Angular dependence of the dHvA frequencies in $CeCoGe_3$ is shown for the magnetic field rotated from [001] towards [100] direction. Only fundamental frequencies are shown. The new frequencies A and B are shown as closed symbols.

the amplitudes of A and B oscillations are still relatively small, the effective masses must be small too. The new frequencies, if present, should therefore be possible to observe at lower field. An appealing possibility is a decrease of the Dingle temperature at high field. Since the oscillatory amplitude depends exponentially on the Dingle temperature, the oscillations might be too small to detect at low field, but become "visible" at higher field where the Dingle temperature is lower. Such scenario is indeed realized in $CeCoIn_5$,[17] where some of the dHvA frequencies are detected only at high field above an abrupt change of the Dingle temperature. Nonetheless, if the new frequencies exist, even if experimentally undetectable, already at low field, it would be difficult to explain their absence in theoretical band structure calculations at least for $LaCoGe_3$, where neither magnetic order nor $4f$-electrons complicate the picture. Moreover, the Fermi-surface cross-sections corresponding to both frequencies do not exceed the area of the Brillouin zone perpendicular to the applied magnetic field. On the other hand, if the emergence of the new frequencies is intrinsically related to high magnetic fields, this would easily account for their absence in the band structure calculations performed for zero magnetic field. If this indeed is the case, the new frequencies certainly do not originate from a magnetic breakdown as there are no two fundamental frequencies that would sum up to yield any of them. Furthermore, the high effective masses observed in $CeCoGe_3$ also rule out such a possibility. Thus, the new frequencies are likely to be an intrinsic property of the compounds and seem to originate from a field-induced modification of the Fermi-surface.

In conclusion, two new high dHvA frequencies have been observed both in $LaCoGe_3$ and $CeCoGe_3$ in high magnetic field up to 28 T. The frequencies are similar in both compounds. Neither of the new frequencies was detected in the previous lower-field measurements or revealed by theoretical band structure calculations. In $CeCoGe_3$, the frequencies correspond to strongly enhanced effective masses implying that they represent thermodynamically important parts of the Fermi-surface. While it is not certain if the frequencies appear in high magnetic field only or simply experimentally undetectable at lower field, they certainly do not originate from magnetic breakdown. They are therefore likely to be intrinsic for both compounds and are possibly due to a field-induced modification of the Fermi-surface.

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